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EXPERIMENTAL STUDY OF STEADY-STATE AND DYNAMIC PERFORMANCE OF A PROPORTIONAL FLUERIC DIVERTER VALVE

by Milton J. LeRoy, Jr.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1967

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SUMMARY

A proportional flueric diverter valve, designed to handle an air flow of 4 pounds per second, was tested to determine its steady-state and dynamic characteristics. Steady-state performance of the valve is presented for a range of supply flows and discharge restrictions (load). Dynamic performance was investigated by frequency response testing.

Steady-state test results showed that maximum flow recovery decreased with an increase in load but was independent of supply flow. Flow gain decreased with increasing load or supply flow. Valve operating characteristics with respect to linearity and hysteresis were very good. Dynamic performance during frequency response tests produced a constant amplitude ratio to 15 cps and a phase lag linearly increasing with frequency. In this frequency range, therefore, the transfer function was that of dead time (0.019 sec).

INTRODUCTION

In the new technology called "fluerics", components have been developed that perform functions of control using a fluid medium and without the use of moving mechanical parts. Because of the apparent dependability of such components, they appear attractive for space applications. In particular, they appear attractive where control systems would have to operate unattended for long periods of time without mechanical failure or leakage problems under extreme environmental conditions of temperature, vacuum, shock, vibration, and nuclear radiation. Most flueric components, however, make inefficient use of the supplied power. The development work in fluerics, therefore, has been largely concentrated on devices for the low-power control functions such as sensing and computing, rather than on devices, such as valves, that handle significant power levels. There are some applications, however, in space power systems, for which flueric valves can be considered since their inefficiency would not seriously detract from the overall power-system efficiency. One such application is the use of a flueric diverter valve between the pump and the boiler of a large Rankine-cycle system (ref. 1). This valve would be part of the turboalternator speed control. Another possible application is in heat-rejection-loop flow control. The need for such control in Rankine systems is discussed in reference 2. Still another possible application is for radiator temperature control in auxiliary cooling loops. The use of flueric valves for this application is discussed in reference 1.

Previous work in flueric valves has, in the main, used the operating principles of either beam deflection or vortex fluidic amplifiers. In fact, large valves based on the beam-deflection principle have already been manufactured (ref. 3). Another type of flueric amplifier that appears promising for valve applications is the double leg elbow amplifier. High mass flow gains with low noise have been reported for small versions of this amplifier (ref. 4). The purpose of the work reported herein was to experimentally investigate the steady-state and dynamic characteristics of a large flueric diverter valve based on the double leg elbow amplifier.

The investigation was exploratory in nature, the intent being to study the capability of a large valve of this type to perform in the manner necessary for a valve in a closed-loop control system. Such characteristics as linearity, gain variations, flow recovery, and dynamic response were of primary interest. No attempt was made to optimize the design of the valve in regard to configuration or power efficiency. The valve was tested on air at Lewis Research Center where steady-state tests were conducted for a range of supply flows and discharge restrictions. Frequency response tests were employed to determine the dynamic characteristics of the valve.

SYMBOLS

A	amplitude ratio of load leg exit flow to inlet control flow, normalized to steady-state conditions
F_C	control flow ratio, $w_c/(w_s + w_c)$
F_R	flow recovery, $w_o/(w_s + w_c)$
f	frequency, cps
G_F	flow gain, ratio of change in load leg flow Δw_o to given change in control flow Δw_c
P	static pressure, psia
P_R	pressure recovery, $(P_o - P_b)/(P_s - P_b)$

s complex operator

w weight flow rate, lb/sec

Δ incremental quantity

τ dead time or transport lag, sec

θ phase shift, deg

Subscripts:

b bypass leg outlet

c control

o load leg outlet

s supply

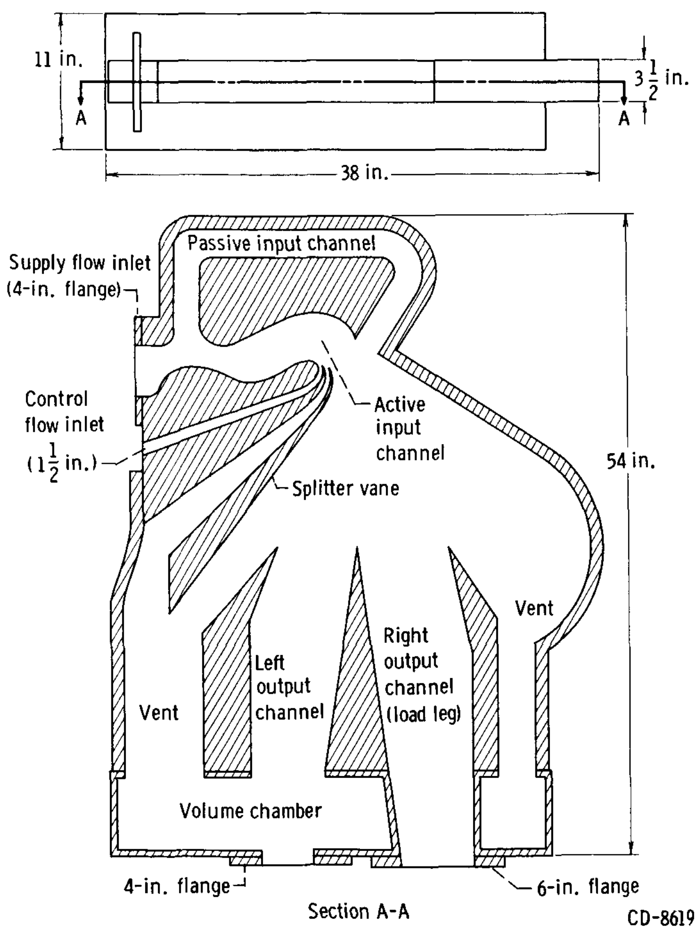

Figure 1. - Representative cross section of diverter valve.

DIVERTER VALVE DESCRIPTION

The diverter valve was designed and built by Giannini Controls Corporation under contract from Lewis Research Center. The valve has no mechanical moving parts, and the flow through the valve can be divided between two output channels in proportion to a small control flow. A schematic diagram of the valve is shown in figure 1. The basic parts of the diverter valve are (1) active input curved channel or elbow, (2) control flow duct, (3) passive input channel, (4) splitter vane, (5) volume chamber and vents, and (6) two output channels. The main inlet flow (supply flow) is divided so that approximately two thirds of the flow travels through the active input curved channel. As this fluid flows in the curved channel or elbow, it tends to separate from the inner wall at a certain point depending on the geometry of the curvature. A small control flow is inserted at the elbow to alter the point of separation and vary the distribution of the main flow between two output channels. Flow through the passive channel is used to deflect the active leg flow into the left exit channel when control flow is zero. The splitter vane is used to form the velocity profile of the active channel. The volume chamber is a pressure balance device which allows movement of the power jet between output channels for proportional control (ref. 4).

The diverter valve was designed to handle an air flow of 4 pounds per second at supply conditions of 40 pounds per square inch absolute and 60° F. The overall dimensions of the valve are 54 by 38 by 11 inches, and it weighs approximately 200 pounds.

APPARATUS, INSTRUMENTATION, AND TEST PROCEDURE

Steady-State Testing

A schematic diagram of the test rig used during steady-state testing of the diverter valve is shown in figure 2. Dry air at approximately 55 pounds per square inch absolute

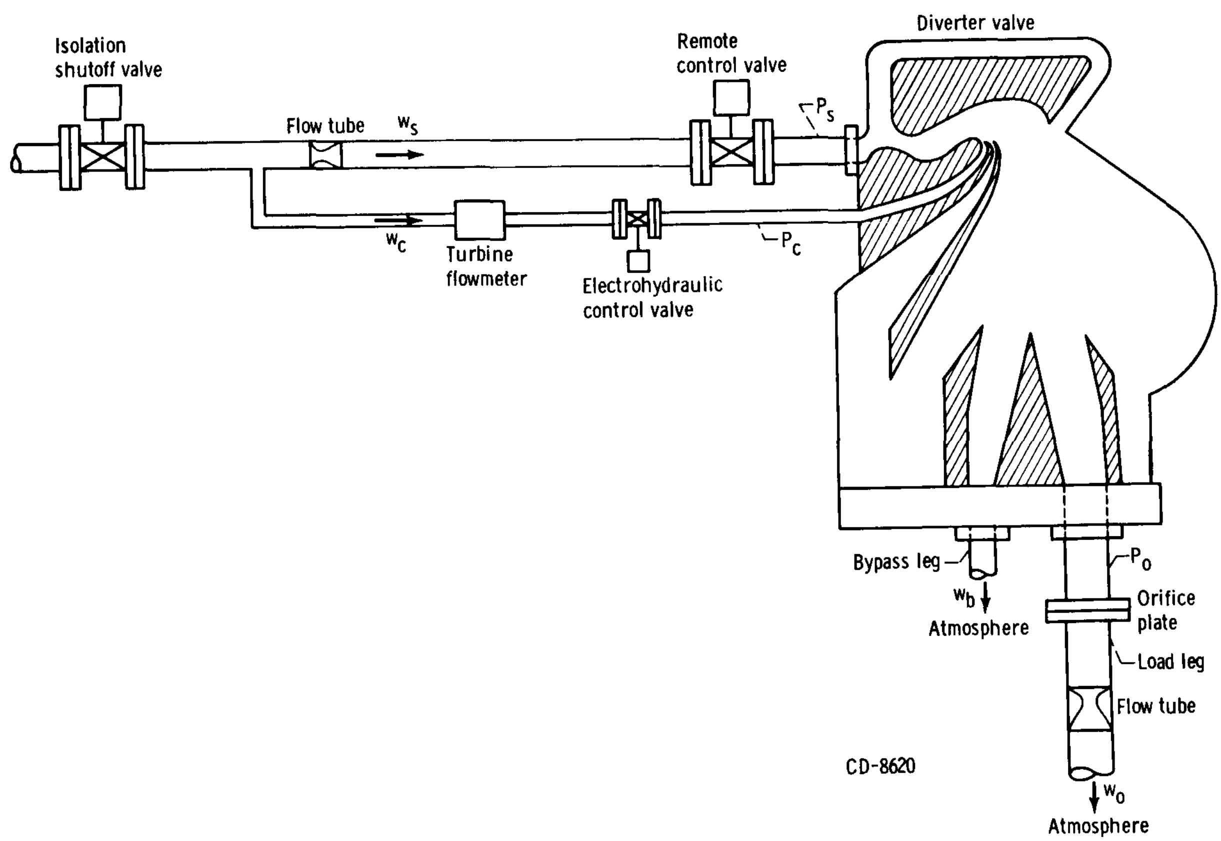

Figure 2. - Test rig used to determine steady-state characteristics of diverter valve.

and 60° F was supplied from the laboratory air system. The supply air flow to the diverter valve was measured by a variable head flow tube and was regulated by a remotely operated 4-inch valve. Control air flow to the diverter valve was measured by a $1\frac{1}{2}$-inch turbine flowmeter and was controlled by an electrohydraulically actuated valve system. The exit flow from the diverter valve load leg was measured by a low-pressure-drop, variable-head, flow tube before exhausting to atmosphere outside the test cell. Exit flow from the diverter valve bypass leg was exhausted directly into the test cell.

All pressures were measured from wall-static taps with strain gage pressure transducers (see fig. 2 for locations) and were recorded on an oscillographic recorder. Differential pressures across the flow tubes were measured with manometers and were also recorded on the oscillograph through strain gage differential pressure transducers. Control flow passing through the turbine flowmeter was indicated on a frequency counter and also recorded on the oscillograph.

During steady-state tests, the supply flow was set at a predetermined flow rate by the 4-inch remotely operated valve. The control flow was varied from zero to approximately 11 percent of supply flow in incremental steps by regulating the electrohydraulic control valve. Orifice plates of various throat diameters were inserted in the load leg piping, 6 inches downstream from the diverter valve exit to determine load (back pressure) effects on the performance of the valve. The orifice plates used during tests had orifice areas of 11.79, 10.32, and 9.28 square inches which reduced the load leg exit area by 67, 58, and 52 percents, respectively. The valve design was based on the load area of 9.28 square inches.

Dynamic Testing

The test rig used during dynamic testing of the diverter valve was the same as that used during steady-state testing with the exception of the load leg piping (fig. 2). The piping downstream from the orifice plate (including the flow tube) was removed to minimize dynamic effects on the load leg flow measurements. Thus, the flow through the diverter valve load leg was exhausted to atmosphere after going through an orifice plate (9.28-sq in. throat area). A calibration curve of output pressure P_o against flow w_o was obtained from steady-state tests in order that dynamic changes in output flow could be calculated from changes in output pressure.

During dynamic tests, the supply flow to the diverter valve was set at 4 pounds per second by the remote-control valve. Average control flow was set at approximately 7 percent of supply flow so small deviations in control flow resulted in linear response of load leg exit flow. A sinusoidal input signal was inserted into the electrohydraulic actuator of the control flow valve, and the frequency of the signal was varied from 0.1 to 15 cps.

Amplitude of the control flow was approximately ±6 percent of the average control flow or ±0.42 percent of the supply flow. All pressures were recorded on an oscillographic recorder during tests. Pressure transducers were mounted with tubing lengths of less than 2 inches to ensure adequate response.

RESULTS AND DISCUSSION

Steady-State Performance

Unrestricted valve exit. - The diverter valve was first tested with no restrictions at the valve exit and with the supply flow w_s set at 3 pounds per second.

A plot of load leg flow recovery F_R as a function of control flow ratio F_C is shown in figure 3. As shown in this figure, an increase in control flow ratio from 0.06 to 0.08 caused the flow recovery to increase from 0.26 to 1.30 for an average flow gain of 52. Flow recovery greater than 1.0 resulted from a flow reversal in which air was drawn into the valve through the bypass outlet leg. It is also shown in the figure that the valve performance was very linear over the normal operating range (control flow ratios between 0.06 and 0.08).

Effect of load on flow recomvery and flow gain. - Supply flow to the diverter valve was set at 3 pounds per second, and the valve was subjected to various loading characteristics by restricting the area downstream from the exit load leg (fig. 4). As this area

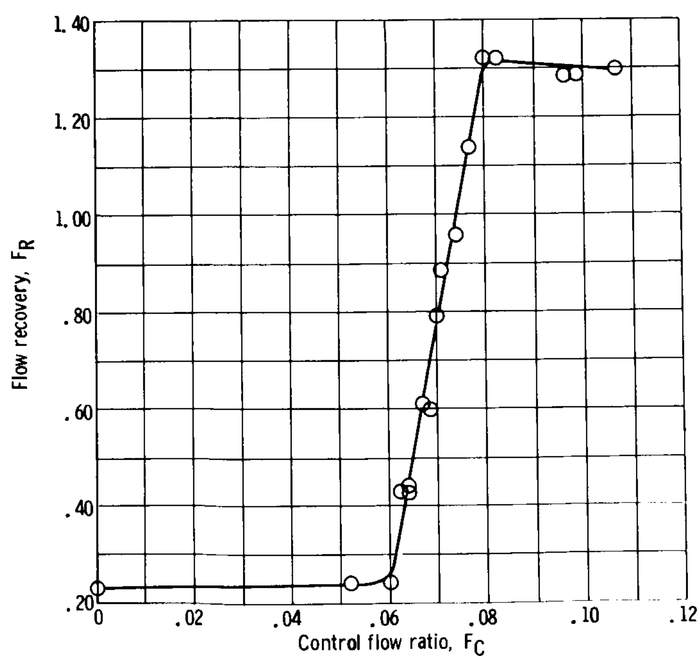

Figure 3. - Variation of flow recovery with control flow. No load on diverter valve; supply flow, 3 pounds per second.

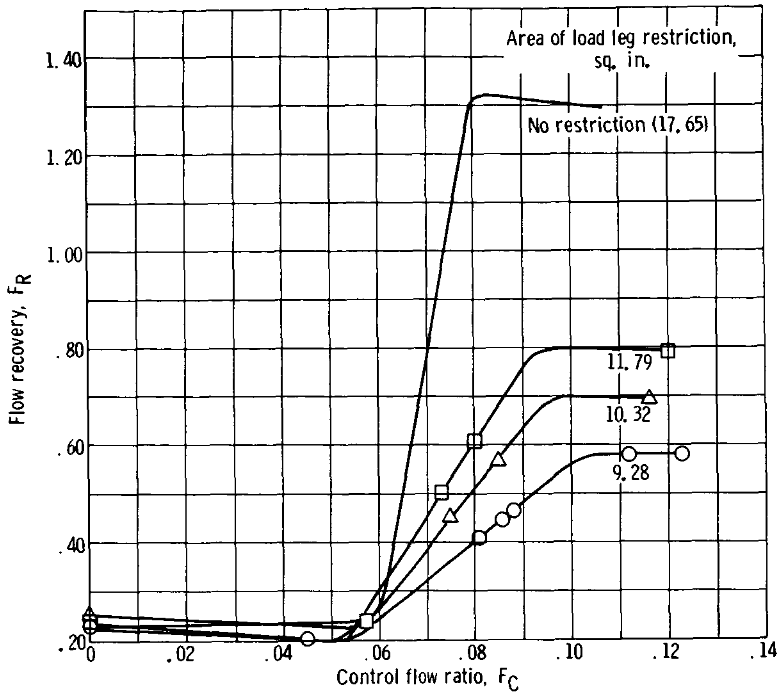

Figure 4. - Effect of load on flow recovery and flow gain at constant supply flow of 3 pounds per second.

was decreased from no restriction (17.65 sq in.) to maximum test restriction (9.28 sq in.), the maximum flow recovery F_R varied from 1.32 to 0.58 and the average flow gain G_F decreased from 52 to 8. Although the average flow gain decreased as load increased; at a constant load, the relation between flow recovery F_R and control flow ratio F_C remained linear to produce a constant flow gain over the normal operating range. The control flow ratio F_C required to reach maximum flow recovery increased from 0.08 to 0.105 as the restriction in the load leg was increased over the range shown. Minimum flow recovery remained approximately constant.

Effect of supply flow on flow recovery and flow gain. - The restriction or load area in the load leg of the diverter valve was kept constant at 10.32 sq in. during these tests, and supply flow was increased from 3 to 4.35 pounds per second (maximum flow due to limitations in inlet piping). Results of these tests are shown in figure 5. Maximum flow recovery remained approximately constant (0.70), but flow gain decreased from 12 to 4.5 as supply flow increased from 3 to 4.35 pounds per second. An increase in minimum flow recovery from 0.255 to 0.40 was encountered when supply flow was increased over the design supply flow (4 lb/sec). This is attributed to insufficient passive flow in the diverter valve. Except for this overdesign case, the linearity was unaffected by supply flow.

Performance with design values of load and supply flow. - The relation between flow recovery and control flow ratio with the design load area of 9.28 square inches in the load

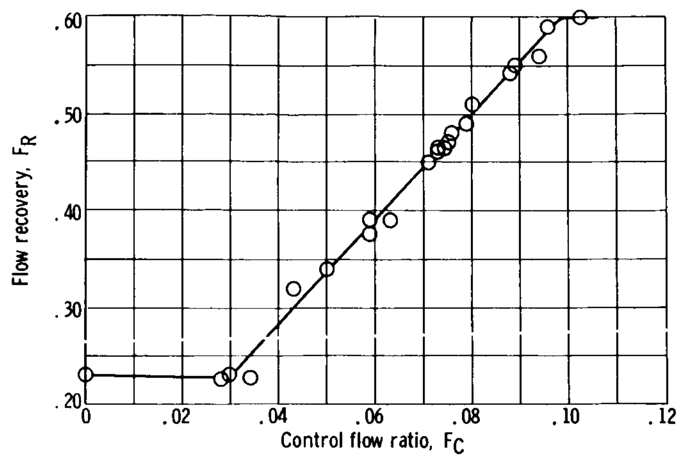

Figure 6. - Valve performance with design values of load (9.28 sq. in.) and supply flow (4 lb/sec).

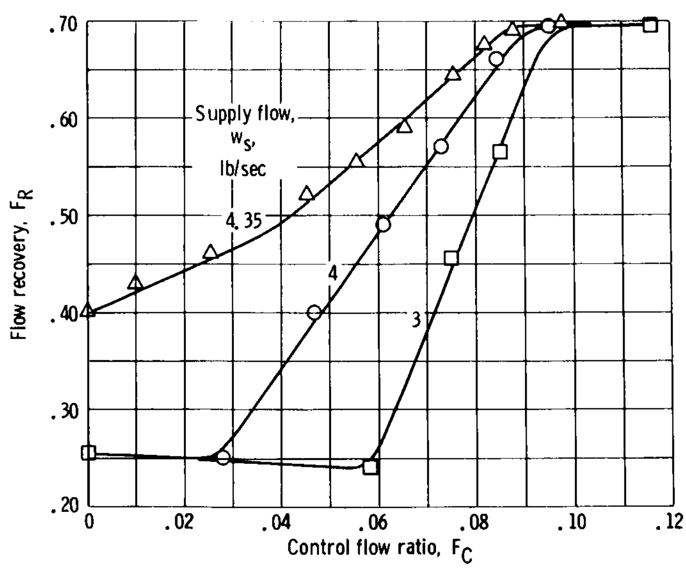

Figure 5. - Effect of supply flow on flow recovery and flow gain with constant load area of 10.32 square inches.

leg and a supply flow of 4 pounds per second is shown in figure 6. During testing, the supply flow remained approximately constant (less than 2 percent deviation) as control flow was changed. Hysteresis in the valve operation was negligible over the total range of control flow ratios investigated.

The following is a summary of the test results with design values of supply flow and load:

Supply flow to diverter valve w_s, lb/sec	4.0
Load leg exit restriction, sq in.	9.28
Minimum flow recovery F_R at zero control flow	0.23
Maximum flow recovery F_R at maximum control flow	0.60
Minimum control flow ratio F_C required to increase load leg flow	0.03
Minimum control flow ratio F_C required for maximum load leg flow	0.10
Average flow gain G_F	5.3
Supply pressure P_s at maximum flow recovery, psia	30.2
Load leg exit pressure P_o at maximum flow recovery, psia	18.2
Pressure drop across valve at maximum flow recovery, psi	12.0
Pressure recovery P_R at maximum flow recovery	0.226

At the design loading on the valve, maximum flow recovery was 0.60. The pressure recovery at this maximum flow recovery was 0.226; however, no attempt was made to optimize this characteristic in the design.

Dynamic Performance

Results from the frequency-response tests are shown in the Bode plot of amplitude and phase shift (fig. 7). As the frequency of the input signal into the diverter valve varied from 0.1 to 15 cps, the amplitude ratio $(\Delta w_o/\Delta w_c)$ remained approximately flat to 15 cps (amplitude ratio was normalized to steady-state conditions). Results from frequencies above 15 cps were not obtainable because of limitations in test instrumentation. The phase shift varied from 0° at 0.1 cps to approximately -100° at 15 cps. The phase shift data agree approximately with the phase shift of a dead time, or transport lag, of 0.019 seconds as shown in figure 8. From these frequency response results, the transfer function $(\Delta w_o/\Delta w_c)$ of the diverter valve is $5.3\ e^{-0.019S}$ for frequencies up to 15 cps and with a supply flow of 4 pounds per second and a load leg restriction of 9.28 square inches.

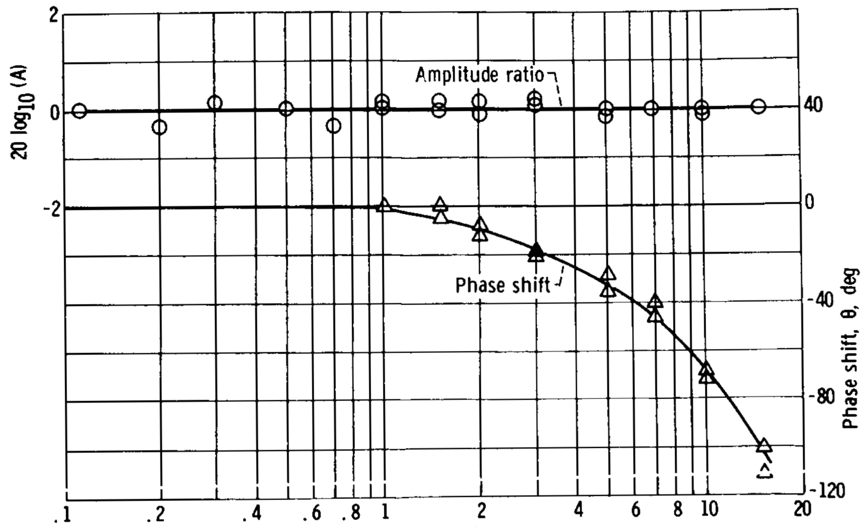

Figure 7. - Bode diagram for diverter value.

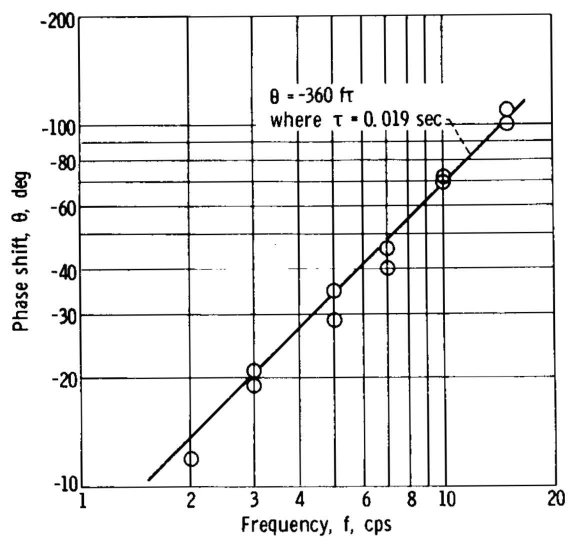

Figure 8. - Comparison of phase shift data with phase shift of dead time (transport lag) τ = 0.019 second.

SUMMARY OF RESULTS

A proportional flueric diverter valve, designed to handle an air flow of 4 pounds per second, was tested to determine its steady-state and dynamic characteristics. The results from steady-state testing of the diverter valve are summarized as follows:

1. Maximum flow recovery of the diverter valve decreased with loading at the valve exit but was approximately independent of supply flow.

2. The flow gain decreased with loading at the valve exit and with increasing supply flow. However, at a given load leg restriction, the gain remained approximately constant over the operating control range of the valve. The gain was also constant at a given supply flow, except for overdesign values.

3. The supply flow was not significantly affected by changes in control flow; thus, the valve action was approximately a pure diverting type.

4. Hysteresis in the valve operation was negligible.

The results of dynamic testing reveal that the frequency-response amplitude ratio of the diverter valve (output flow to control flow) remained constant to at least 15 cps, while the phase lag linearly increased with frequency. Thus, the transfer function from 0.1 to 15 cps is simply that of a dead time (0.019 sec).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 15, 1966,
701-04-00-08-22.

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